SPACESHIP NEUTRINO

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Introduction

Neutrino physics is largely an art of learning a great deal by observing nothing.[1]

Haim Harari, 1988.

ON 23 FEBRUARY, 1987, a hoard of billions upon billions of extragalactic messengers swept through the Earth. Only a few stopped at our rocky planet; the vast majority continued onwards, unperturbed on their journey across space.

The messengers were *neutrinos*, subatomic particles with few measurable properties, barely more than pieces of nothing. Yet neutrinos are one of the dominant forms of matter in the Universe, outnumbering the more familiar particles of atomic nuclei by a billion to one. Neutrinos produced in the Big Bang, the explosive event from which our Universe appears to have grown, permeate every cubic centimetre of space. Moreover, the Sun bathes our planet with neutrinos just as it bathes it with sunlight. Hold out your hand as if to catch them and, whether it is night or day, each second ten thousand billion solar neutrinos will pass through it.

Like the Sun, all stars emit neutrinos, but the extragalactic neutrinos that swarmed through the Earth early in 1987 marked a special event. Some 170 million years ago, in a nearby galaxy called the Large Magellanic Cloud, a star nearly 20 times the size of the Sun died in a catastrophic explosion, flinging subatomic debris out into space. On 23 February, 1987, the first signals from the explosion reached Earth – myriads of neutrinos bearing witness to the death of the distant star. A few hours later, astronomers in the Southern Hemisphere saw the first light from the explosion, heralding the appearance of SN1987A, the first supernova to be visible to the naked eye for 400 years.

The detection of only a few of the neutrinos from the supernova marked the beginning of a new branch of observational astronomy. It also reinforced the growing relationship between particle physicists, who study the small-scale, barest essentials of matter, and astrophysicists and cosmologists who study the workings of the Universe at large. Neutrinos form a substantial, albeit almost invisible, bridge between one of the oldest sciences, astronomy, and one of the newest, particle physics. Whereas astronomy has its roots in antiquity, particle physics emerged as a full branch of science only in the early 1950s, the progeny of research into the structure of the atom. My intention in this book is to show how neutrinos came to play a leading role in particle physics, eventually forging links to astronomy and cosmology in a variety of fascinating ways.

Anyone who is familiar with the basic ideas of particle physics can now turn quickly to the beginning of Chapter 2. Others may welcome the brief description that follows here of the place of neutrinos in particle physics. I have attempted to introduce the necessary concepts at appropriate places in later chapters, nevertheless some of you may find it helpful to be given some preliminary guidance as you embark on your journey into the realm of neutrinos.

During the first decade of the twentieth century, physicists discovered that atoms consist of a tiny, central positively charged nucleus, surrounded by a cloud of negatively charged electrons. They went on to learn about the structure of the nucleus and found that it is built from positive particles, which became called protons, and neutral particles, which were dubbed neutrons. The charge on the protons exactly balances that on the electrons, so that a complete atom, in which the number of electrons equals the number of protons, is electrically neutral. But in most other respects, protons and neutrons differ dramatically from electrons. Most noticeably, protons and neutrons are much heavier, being around 2000 times as massive as electrons.

In the world about us, protons, neutrons and electrons combine together to form more than 90 different kinds of atom, each unique to a specific chemical element. From these foundations stems Earth's great diversity, as atoms of different elements react together to make compounds – water, for example, consists of hydrogen and oxygen atoms locked together in precise proportions, while vastly more complex structures of hundreds of atoms form proteins, the building blocks of life itself.

Most of the matter on Earth is completely stable, but some atoms are intrinsically unstable – we say they are radioactive, because they radiate energy as they change from one form to another. Radioactivity, discovered late in the nineteenth century before the structure of the atom had been unravelled, is a natural phenomenon, occurring, for example, to varying degrees in the rocks beneath our feet.

In all types of radioactivity the underlying process is the same: an atomic nucleus spontaneously changes to a less energetic state, emitting the excess energy as it does so. This energy emerges as radiation – sometimes as gamma-rays, a highly energetic form of light; sometimes in the form of alpha-particles, which are ultra-stable configurations of two protons and two neutrons; and sometimes as pairs of electrons and neutrinos. The neutrinos

Wolfgang Pauli (1900–58) – 'father' of the neutrino. (AIP Niels Bohr Library, Goudsmit Collection.)

produced in this way contribute billions to the swarms that traverse our environment.

It was studies of radioactivity that led to the first suggestion of the existence of the neutrino in the early 1930s. Investigations of the radioactive transmutations that emit electrons suggested that some of the energy was missing. Wolfgang Pauli, a brilliant Austrian theorist, proposed that an electrically neutral, lightweight, very feebly interacting particle must take away some of the energy released. Two decades later, researchers in the US finally succeeded in observing these particles through their extremely rare interactions with matter. And so began experiments with neutrinos, which have led not only to observations of neutrinos from the Sun and the supernova SN1987A, but also to investigations of subatomic particles and their forces. One of the most paradoxical features of these extraordinary particles is that although they are so difficult to detect, passing readily through the Earth without interacting, they have revealed vital information about almost all aspects of subatomic particle physics.

That neutrinos can be detected at all is due to the fact that they *can* interact occasionally with other subatomic particles, through the agency of one of nature's fundamental forces, the *weak force*. This is the force that underlies the radioactive transitions that lead to the emission of electrons and neutrinos. In atoms, the weak force is at least 1000 times more feeble than the electromagnetic force, which acts between charged particles and keeps the atom bound together. And it is a 100 000 times weaker than the *strong force*, which binds protons and neutrons together in the nucleus.

The weakness of the weak force means that neutrinos can travel cosmic distances without interacting with other matter. But fortunately for physicists, the whole process is rather like life itself. In developed countries most of us have a good chance of surviving at least our 'three score years and ten'. However, some people live for only a few years, while others can last a century a more. So it is with neutrinos travelling through a large detector. While the likelihood is that a neutrino will travel through the detector unaffected, there is a small but real probability that it will interact through the weak force with one of the subatomic particles in the material there. By studying these weak interactions of neutrinos, particle physicists have learned not only about the neutrinos themselves, but also about the particles with which they interact and the force through which they interact.

In the 1970s, experiments with neutrinos, in addition to complementary experiments with electrons, revealed a new level of subatomic matter. It turns out that protons and neutrons are not themselves fundamental, but consist of smaller particles, the *quarks*. The quarks are bound by the strong force within the protons and neutrons, and while single quarks cannot be knocked out of the larger particles, it is possible to 'see' them inside the protons and neutrons by sending in neutrinos or electrons. Rather as radar reflections reveal aeroplanes or ships hidden in dense fog, so the scattering of neutrinos or electrons reveals the tiny quarks buried deep within protons and neutrons.

So far there is no experimental evidence for structure within quarks themselves, and it is possible that they are truly fundamental building blocks of matter. Similarly, electrons and neutrinos appear to be simple, structureless particles, differing from the quarks only in that they do not feel the strong force. Over the past two decades, the idea has grown that there are two distinct 'families' of fundamental particles: those that feel the strong force – that is, the quarks – and those that do not, which are called *leptons*.

The existence of matter here on Earth depends on two kinds of quark, required to build protons and neutrons, and two kinds of lepton – the electron and its related neutrino, which is emitted in radioactive decays. But as long ago as the 1930s studies of cosmic-rays began to show that Nature requires more particles than the four needed here on Earth. Cosmic-rays are energetic particles, including neutrinos and gamma-rays, which stream down through the atmosphere. While many of the neutrinos originate with the Sun, or cataclysmic events such as SN1987A, other neutrinos, and many charged particles, are produced in nuclear reactions that occur when very energetic particles from outer space (mainly protons) collide with atoms in the upper atmosphere.

Most of the charged particles produced in the atmosphere are short-lived and decay, rather as radioactive nuclei do. After only several billionths of a second, they transmute to more stable particles, eventually yielding electrons, protons and neutrinos. These short-lived particles can also be produced in controlled conditions here on Earth, in experiments at laboratories that house particle accelerators. These machines take beams of particles, such as protons or electrons, and feed them energy from electric fields, accelerating them to velocities close to the speed of light. When the

Experiments with high-energy neutrino beams at CERN, the European centre for research in particle physics, have made several important discoveries about the fundamental particles and forces. The laboratory lies on the northern outskirts of Geneva, the main site occupying the centre foreground on this aerial view which is looking south towards Mount Blanc. (CERN.)

energetic particle beams strike matter, they produce new short-lived particles, just as in the cosmic-ray collisions in the atmosphere.

Studies of these short-lived particles have shown that there are more kinds of quark than are needed to build protons and neutrons, and more types of lepton over and above the electron and its related neutrino. At present all the evidence points to there being six types of quark, and six types of lepton, of which three are charged (and include the electron) and three are neutral. All three types of neutral lepton are called neutrinos.

The interactions of all these particles through the strong, weak and electromagnetic forces are described within a theoretical framework known as the *Standard Model*. During the 1970s, neutrino experiments at particle accelerators played an important part in establishing this model, which describes very well the interactions of the fundamental quarks and leptons. Yet good as it is, the Standard Model has many shortcomings. For example, it does not include the fourth fundamental force, gravity, nor does it explain why the masses of quarks and leptons are what they are. Neutrinos of all three types have masses far smaller than their charged lepton counterparts, but are their masses indeed zero? Experiments so far cannot say for sure, and the Standard Model cannot tell us.

The role of neutrinos as tools of particle physics is not yet over, for they will almost certainly help to guide theorists in improving the Standard Model, just as they helped to reveal the nature of quarks and the weak force. But with the detection of neutrinos from SN1987A, these remarkable particles are also becoming tools for astronomers. Neutrino 'telescopes' may, over the next decade, reveal the source of ultra-high energy cosmic-rays, long a puzzle to astrophysicists.

Neutrinos, which are about as close as something can come to being nothing, can not only tell us about much of particle physics but can also provide a unique window on astrophysics and cosmology. This book will take you on a tour of the ways in which physicists have learned so much through studying neutrinos and of the struggles involved. Some of it, like neutrino experiments themselves, will not be easy, but I hope that like the experimenters, you will persevere and come to regard neutrinos with the same fascination that I, and many others, have for these elusive particles. The journey is going to take you to the heart of the atomic nucleus, deep into outer space, and back in time, not only to the early days of the twentieth century, but also to the origins of the Universe. I hope that it is a journey that you enjoy.